Electrical characteristics of cold ironing energy supply for berthed ships

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Abstract

The reduction of emissions in harbours is of particular importance due to the proximity to human habitation. Vessels normally run onboard generators, typically using diesel fuel, to provide the service loads while berthed. New and upcoming regulations aim to decrease emissions from shipping, and coupled with increased environmental consciousness of ship owners and harbour operators, shore supply is becoming a more popular and feasible option. Cold ironing provides an alternative locally emission-free solution by having berthed ships plug in to the shore electrical network, such that the onboard electrical energy demand is supplied from land. Electrically, a number of different shore network topologies are possible, providing different infrastructural options of supplying power to multiple berths. This paper examines the electrical characteristics of one such installation and the impact on the shoreside electrical network for an existing port using actual visiting ship power profiles. The paper examines how the cold ironing system influences important electrical network characteristics such as bus voltages and power quality, as well as the potential impact on the rest of the utility distribution system.

Keywords

Onshore power supply, cold ironing, power quality, frequency converter, marine power systems

1. Introduction to onshore power supply

Ships are currently responsible for moving about 80% of the world's trade (by volume) and contribute about 2.7% of the total manmade CO_2 emissions worldwide. With current and predicted growth rates, this implies a corresponding increase in airborne emissions by shipping if no measures are taken to reduce the environmental impact of vessels (Chang, 2012). Airborne emissions have a direct impact both on human health as well as the environment, which arise from the combustion of fossil fuels onboard vessels, typically in diesel engines used both for propulsion as well as onboard power generation (McArthur and Osland, 2013; Prousalidis et al., 2014).

The operation of the onboard generators can be minimised by connecting vessels to the shore electrical supply (a practice known as cold ironing) such that the power requirement is met by land based generation, supplying the electrical energy from a centralised source. This gives a locally emission-free solution, though the resultant overall airborne emissions will be a function of the generation mix employed on land (Chang and Wang, 2012; Hall, 2010; Zis et al., 2014). Legislation, both current and upcoming, aims to incentivise and promote the uptake of cold ironing systems and reduce the emissions generated at berth. Within EU ports, the Sulphur Directive (The European Parliament and the Council of the European Union, 2012) limits the Sulphur content of fuels used by ships in EU ports to less than 0.1% by mass when the scheduled stay is longer than two hours. Ships which shut down all engines and use a shore electrical supply are considered compliant. A similar Sulphur limit is in place since 1 January 2015 in Emission Control Areas (ECAs), with a global Sulphur limit being reduced from 3.5% to 0.5% in 2020 (or 2025 pending a review in 2018) (International Maritime Organization, 2005). Shore supply is a solution to meeting these limits while berthed in harbour, providing an alternative to the use of expensive, low sulphur content fuel (Zis et al., 2014).

At the same time as increasingly stringent environmental requirements, newly developed technical standards aim at facilitating the expectations and requirements for both port operators as well as visiting vessels, by setting out the required components as well as quality of supply expected at the berths. Joint standard IEC/ISO/IEEE 80005-1 sets out the requirements for High Voltage Shore Connections (HVSC) (IEC/ISO/IEEE, 2012), while IEC/IEEE 80005-3 (pre-standard) deals with Low Voltage Shore Connections (LVSC) (International Electrotechnical Commission, 2014) for vessels with a lower power demand based on similar concepts, such as the location of the frequency converter on shore and the need for galvanic isolation for each connection.

Significant investment is required on the shoreside in order to provide the necessary infrastructure for shore connection. Fundamentally, the shore supply is expected to provide a suitable power supply able to meet the ship onboard requirements. Additionally, the supply must be able to provide the necessary extra power demand, possibly involving installation or upgrading of port area substations (Khersonsky et al., 2007). One of the main challenges is the need for power to be provided at 50 or 60Hz as demanded by the berthed vessel, requiring a frequency converter if the shore and onboard frequencies do not match. This is especially of relevance to European and Asian ports, where 50Hz is generated on shore, while the majority of ocean going vessels operate at 60Hz (Ion et al., 2013). The generic infrastructural requirements of a cold ironing supply according to IEC/ISO/IEEE 80005-1 are outlined in Figure 1.

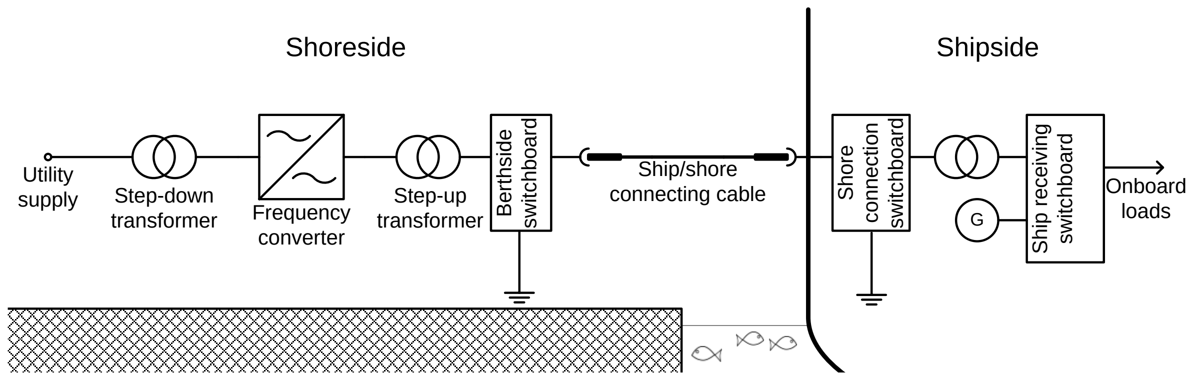

Figure 1. Generic requirements of cold ironing system.

Within the scope of the technical requirements of the standards and extending from the generic system of Figure 1, different electrical topologies are possible in order to deliver sufficient power of the necessary quality as required by each berth (Ericsson and Fazlagic, 2008; Sciberras et al., 2014).

The location and topology of the frequency conversion system is the chief variation in these, i.e. whether a single frequency converter is centrally located to provide 50/60Hz or whether a distributed topology is more suited, with a converter for each connection.

A number of electrical issues, especially in terms of protection and safety, are of concern to shore connection installations. In (Sulligoi et al., 2012), the authors discuss the dangerous touch voltages created in the case of a ship connected to the shore supply with a phase to ground fault in the system, arising because of a common earthing situation. Grounding is also discussed in (Paul and Chavdarian, 2009), while (Paul et al., 2011) looks at the more specific aspect of residual charge in the ship-to-shore cable and the need for a grounding switch. Surge protection is discussed in (Paul and Haddadian, 2011) outlining the need for surge arresters both on shoreside as well as onboard, with the grounding configuration determining type and rating of the protective devices. An additional protective concern is the short circuit current capability of the installation, which is addressed in (Ion et al., 2013). Common to all these works is the appreciation of the fact that each project is unique, requiring an in depth study for each cold ironing installation.

This work focuses particularly on the operational electrical characteristics of a cold ironing installation, studying the operation of the system and how it affects upstream (the local electricity distribution network) as well as downstream (ship) consumers. The cold ironing system is modelled based on a real scenario profile of a RoRo terminal, considering actual historical loading levels of the berthed vessels. This is used to examine important network power quality issues such as harmonic distortion as well as steady state voltage levels, permitting a detailed analysis to be carried out of the impact of the cold ironing installation on the local electricity network.

2. Cold ironing system

The selection of circuit topology is a key part of the shore network design which must be matched to the expected power demands of the berthed ships. As part of a collaborative project with a harbour in North-West Spain, the port's data about vessel visits, together with their power demands was used to build a picture of the typical load profile seen by the port. This was used in a previous study to build a search algorithm to identify the optimal shore network configuration for providing the required berth power at the lowest emissions, while at the same time minimising the infrastructural costs involved (Sciberras et al., 2014). The port in question consists of a five berth Roll-On Roll-Off (RoRo) ferry terminal which sees a range of 50/60Hz ships with a spread of electrical power demands from around 300kVA to 1.2MVA.

First order models of the various components in the shore power network were modelled in order to be able to give quantitative estimates of the efficiencies of the different systems. These models were concerned with energy losses in the components of the systems involved, and hence focused on fast simulation times, in order to facilitate the consideration of a number of different configurations and setups. Fast events (such as semiconductor device switching) and controller dynamics were approximated by first order models. These gave sufficient detail to quantify power losses for a given operating point. However these models do not give any indication of the actual electrical operation of the system and only account for the power flow study of the network.

Figure 2 shows an example of the actual measured power profile showing the variation in the RoRo vessel load at berth 3. The averaged power profiles at all 5 berths over a typical working week, used to for considering overall energy consumption and losses, are shown in Figure 3. In a previous study (Sciberras et al., 2014), the circuit topology and component ratings giving the least emissions for the port in question were identified by using a Particle Swarm Optimisation (PSO) algorithm in conjunction with the averaged measured berth power profiles. A centralised cold ironing topology was seen as the most appropriate in this case, giving the highest overall efficiency for the lowest resultant shoreside emissions. The optimal cold ironing configuration, as identified in this previous study, is summarised in Table I. When compared to running the onboard generators, the use of the cold ironing supply was seen to reduce CO_2 emissions by about 46% based on the local (Spanish) power generation mix.

The work presented in this paper looks in detail at the electrical characteristics of this centralised cold ironing system and its impact on the local distribution network. The components making up the centralised cold ironing network are shown schematically in Figure 4. Here the central frequency converter supplies a double busbar arrangement which can be used to selectively provide either 50Hz or 60Hz to the berths, as required. High fidelity models are built which look at the detailed behaviour of the system, capturing fast events such as Pulse Width Modulation (PWM) switching, such that the steady state voltages as well as power quality (such as waveform distortion) at the shore connections can be determined. As well as accounting for the various losses in the system, these detailed models permit the network to be examined at various loading levels and conditions, such that the operational electrical characteristics of the circuit can be predicted and the impact on the local supply network assessed.

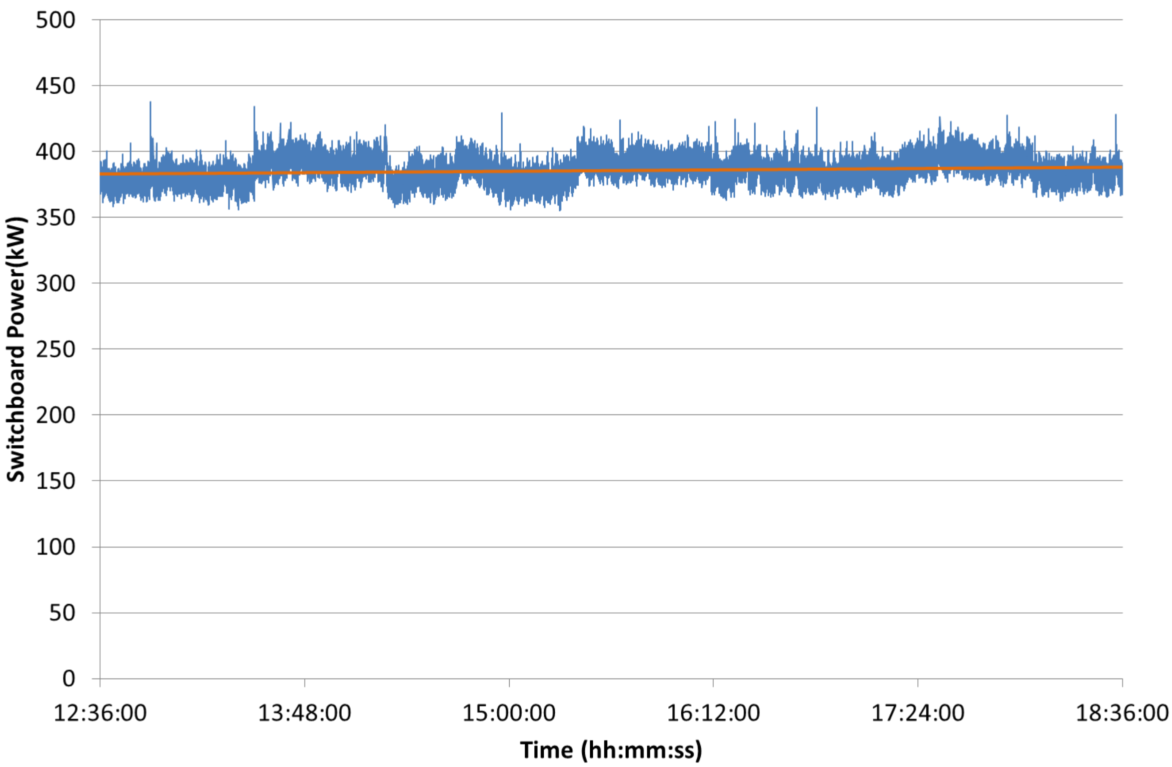

Figure 2. Snapshot of measured and averaged load profile (berth 3).

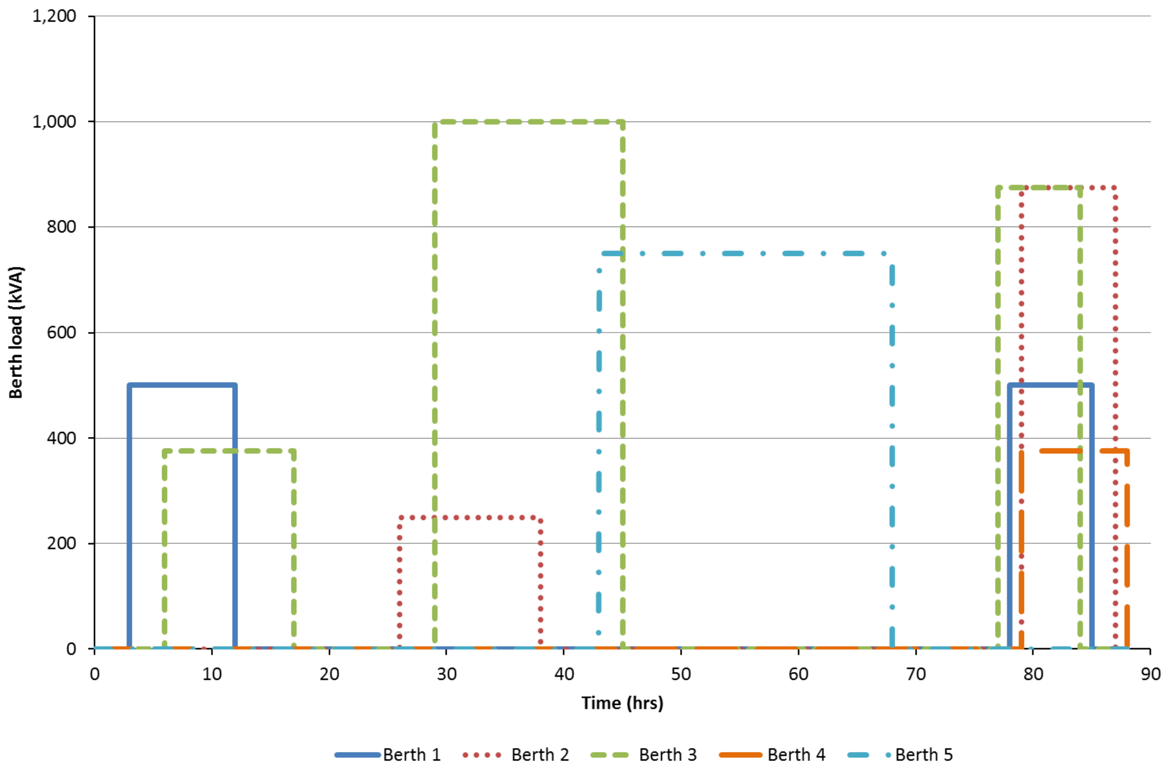

Figure 3. Snapshot of berth power profiles over a typical working week.

Table I. Optimised centralised configuration for shore connection network based on first order model study.

Berth ratings (kVA)						*Overall efficiency*
Berth 1	*Berth 2*	*Berth 3*	*Berth 4*	*Berth 5*	*Central converter*	
700	1000	1050	550	900	2800	89.5%

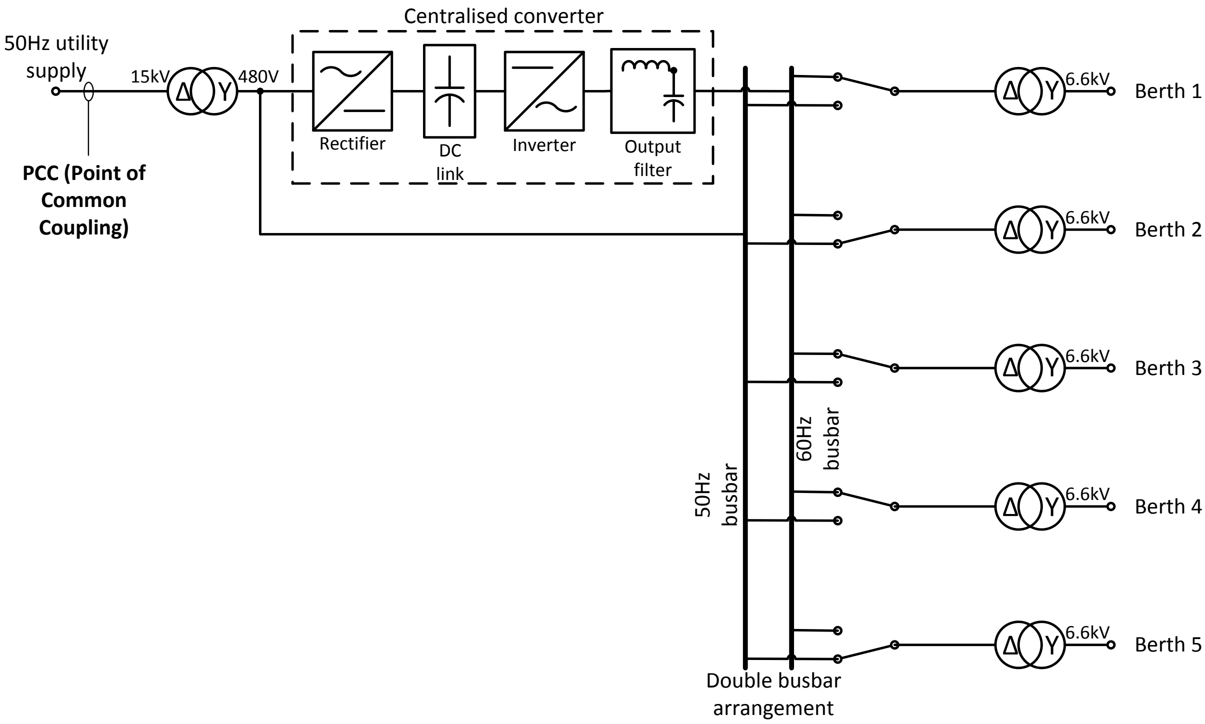

Figure 4. Schematic diagram of centralised shore supply topology.

3. Network power quality

Among the most important electrical characteristics of any power distribution network is the quality of the power delivered to the load. Power quality can be measured by the level of deviation of the voltage supply from the ideal sinusoidal waveform with the desired amplitude and frequency. The connection of a load should not have adverse effects on the supply network. Equally, the supply to any downstream loads should not be negatively affected by any interactions between the load and supply network. In a cold ironing scheme, the quality of supply needs to be examined at the berthside, as berthed ships expect a guaranteed minimum level of power quality, while also ensuring that the operation of the shore connection system does not adversely affect other consumers connected to the same utility supply (IEC/ISO/IEEE, 2012).

An ideal electrical system supplies and draws sinusoidal voltage and current waveforms. However, the presence of power electronic devices creates a non-linear system due to the turn-on and turn-off operations of these controlled switches. Hence the real waveforms observed, consist of a large number of higher order components superimposed on the fundamental 50 Hz or 60 Hz frequency. These higher order components are known as harmonics.

The presence of harmonic currents means that the total Root Mean Squared (RMS) current flowing in the system is higher (for any given load), increasing the Ohmic losses. Furthermore, transformers and other magnetic components suffer from increased losses at higher frequencies, leading to additional power losses. In addition, the presence of harmonic currents will cause a corresponding potential drop across the supply impedance, leading to a distorted voltage at the supply. This results in other consumers being affected by this non-sinusoidal supply. Hence, various standards and requirements are in place to ensure that equipment/systems meet a minimum level of harmonic content. The harmonic content is quantified by the Total Harmonic Distortion (THD), which for a distorted current waveform is defined by Equation 1, where I_h are the individual harmonic components making up the waveform and I_1 is the fundamental waveform. This is measured at the Point of Common Coupling (PCC), which is the point in the power system closest to the user where the system operator could offer service to another customer as marked in Figure 4 (IEEE, 2014).

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \qquad \text{Equation 1}$$

4. Detailed electrical analysis of cold ironing supply

The study of (Sciberras et al., 2014) indicated how a centralised cold ironing topology was the most appropriate for this particular port scenario. In this case, a single frequency converter is centrally located, and by means of a double busbar arrangement (as shown in Figure 4), 50Hz or 60Hz supplies can be provided to the individual berths as required. The advantage of this system is that the expected load diversity of the connected vessels can be taken into account such that the rating of the converter is not necessarily the sum of the total connectable load.

In this paper, a detailed model of the centralised cold ironing topology (Figure 4) was built within the Matlab/Simulink environment. The power profiles of Figure 3 are the operational inputs to the model, which considers power fed from a 15kV utility supply. The component models implement continuous differential equations and piecewise linear models for the switching devices.

A schematic diagram of the frequency converter implemented is shown in Figure 5. Here a diode front end (diode bridge rectifier) is shown, which rectifies the supply to the intermediate DC link. An Insulated Gate Bipolar Transistor (IGBT) inverter is then used to modulate the voltage to provide a three-phase 60Hz output at the desired voltage (Mohan et al., 2003). The output of such a converter is a PWM waveform as shown in Figure 6. This must be filtered before being supplied to a consumer which expects a clean sinusoidal supply.

The control algorithm in Figure 5 implements a vector control strategy to generate the required output voltage waveforms, comprising a cascaded loop control with an outer voltage control loop, and a nested current controller. PI (Proportional and Integral) controllers are used, which are tuned to give the desired dynamic response of the controlled outputs. The Clarke and Park transformations are mathematical transformations which convert three-phase quantities to equivalent constant quantities in a synchronised orientation rotating at the desired output frequency (f* in Figure 5). The corresponding inverse transformations feed the controlled output signals to the PWM generator, the output of which is used to switch on/off each individual IGBT in the inverter.

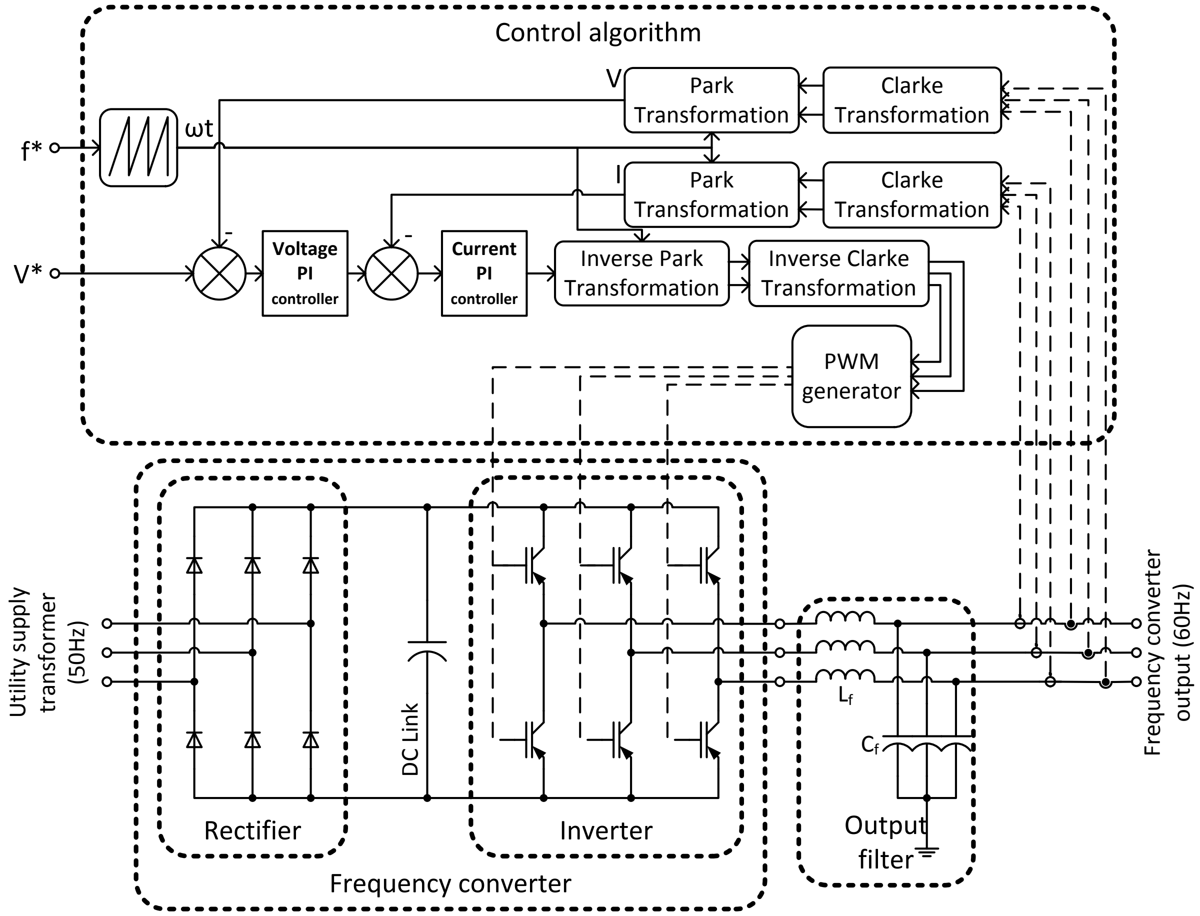

Figure 5. Schematic of frequency converter.

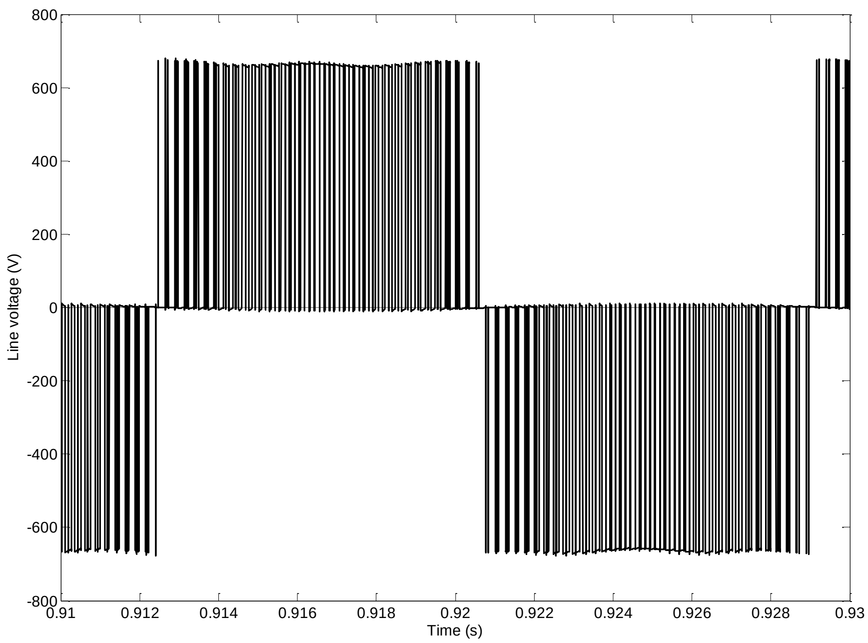

Figure 6. PWM output voltage (line to line).

In Figure 5, a Low Pass Filter is shown at the output of the inverter, which diverts the high frequency harmonic components of the PWM waveform to ground (via the capacitors) providing an output with a substantially reduced harmonic content (compared to Figure 6). A simple inductive (*L*) filter can provide a limited amount of attenuation of high frequency harmonics, but this requires the use of a high switching frequency in the power electronic converter in order to produce an acceptable output. With the addition of a shunt capacitor, an *LC* filter can be obtained tuned for a given corner frequency (Equation 2) (Ahmed et al., 2007). The presence of a series filter component (the inductor L_f) results in a voltage drop when current flows through the filter. Hence the filter design must take into account an allowable voltage drop at the output which must be compensated for by the inverter raising its output voltage (within its limits) in order to regulate the output voltage.

$$f_c = \frac{1}{2\pi\sqrt{L_f C_f}} \qquad \text{Equation 2}$$

For this study, the parameters of the output filter were chosen for a 5% voltage drop and a corner frequency (f_c) of 400Hz, corresponding to a factor of one tenth of the inverter switching frequency of 4kHz, and are listed in Table II together with the value of supply side inductance.

Table II. Component values for frequency converter.

Quantity	Symbol	Value
Supply side inductance	L_s	1.54mH
Supply voltage	V_s	15kV
Voltage PI controller proportional gain	K_{pv}	0.675
Voltage PI controller integral gain	K_{iv}	405
Current PI controller proportional gain	K_{pi}	6.75×10^{-5}
Current PI controller integral gain	K_{ii}	0.054
Switching frequency	f_s	4kHz
Filter inductance	L_f	5.3µH
Filter capacitance	C_f	30mF

The transformer at the input of the converter is used to step down the input medium voltage supply (15kV in this instance) to a low voltage level of 480V, which permits the use of conventional low voltage power electronics. The voltage is then stepped up again at the output in order to provide the voltage level required by the berth connections (6.6kV) (Yang et al., 2011). This transformer also provides the required galvanic isolation if supplying a single berth, otherwise additional isolation transformers are needed for each connection. With developments in transistor technology, high voltage devices will permit high voltage converters to be more commonplace, avoiding the need to step the voltages, reducing the current levels and hence the cabling requirements.

4.1. Operational snapshots

Table III shows a snapshot of the steady state operation of the system. The steady state RMS values of the output voltages for all the berths are within the 3% permitted deviation from the nominal (6.6kV) (IEC/ISO/IEEE, 2012). Figure 7 shows the voltage waveform as supplied to a vessel connected to berth 1 (Figure 4) with a 500kVA load. The frequency spectrum of the Phase A voltage waveform is shown in Figure 8. This shows how some harmonic distortion is still present at the output which would not be discernible from a simple visual inspection of the time domain waveforms. Of interest here are the harmonics (attenuated) around the 4kHz band, which correspond to the sidebands around the switching frequency of the converter. The THD value for this output is 0.66%, and none of the individual harmonics exceeds 3%. The supply to berth 1 is therefore well within the acceptable THD limits. Similar plots are seen for the other berths and other phases, and these results are tabulated in Table III showing how all outputs to all berths are within the acceptable THD limits.

Table III. Nominal loading condition.

Berth number	*Load (kVA)*	*Line Voltage (V)*	*Deviation from nominal*	*Voltage THD at berth*
1	500	6,459	2.1%	0.66%
2	800	6,441	2.4%	0.66%
3	1,000	6,414	2.8%	0.65%
4	350	6,473	1.9%	0.67%
5	700	6,447	2.3%	0.66%
			Input current THD	55.46%
			Voltage THD at PCC	5.33%
			Overall energy efficiency	90.4%

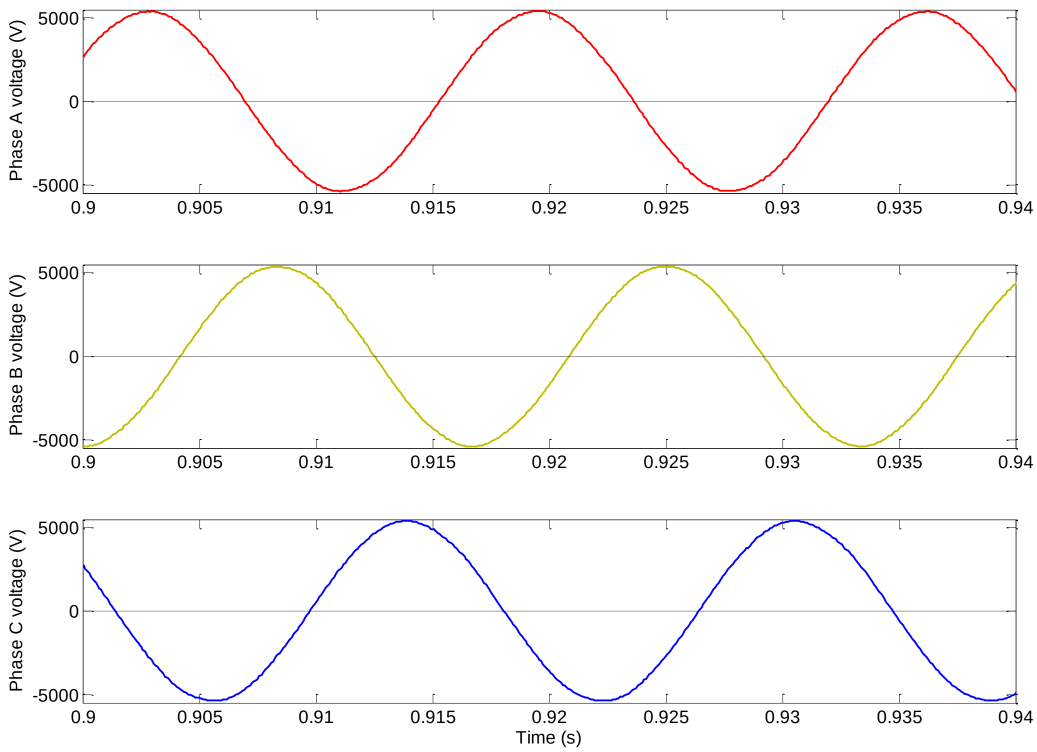

Figure 7. Terminal voltage at berth 1 shore connection.

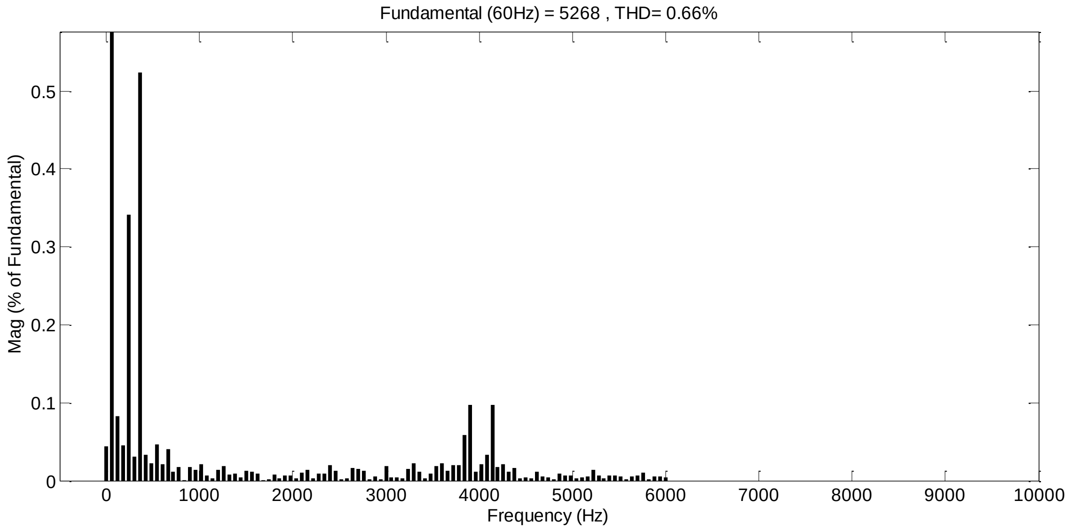

Figure 8. FFT of output voltage at berth 1.

At the supply side, Figure 9 shows the input currents drawn from the utility at the 15kV Point of Common Coupling (PCC) which is the point on a power supply system where other loads would be connected (Figure 4). This clearly shows the six pulse operation associated with the use of a diode bridge rectifier (six pulses of the dc waveforms for every ac supply cycle). This waveform is far from sinusoidal, with a significant 5^{th} harmonic component at 250Hz (for a 50Hz supply), together with additional higher frequency harmonics. Seen in the frequency domain, this is confirmed by Figure 10 which shows the FFT of the input current as measured at the PCC. In this case, the THD is above 50%, with very large low frequency harmonics which exceed the minimum levels as set by standardisation bodies. Table IV and Table V list the acceptable voltage and current THD limits at the PCC as specified by IEEE 519 standard (IEEE, 2014).

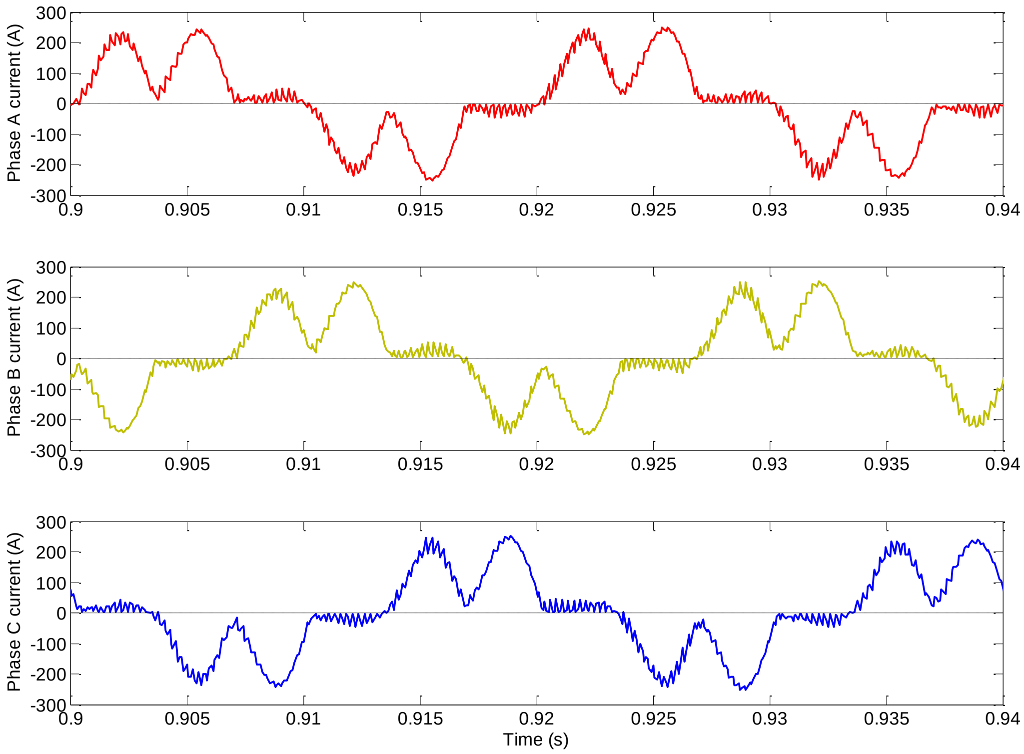

Figure 9. Input current from utility supply.

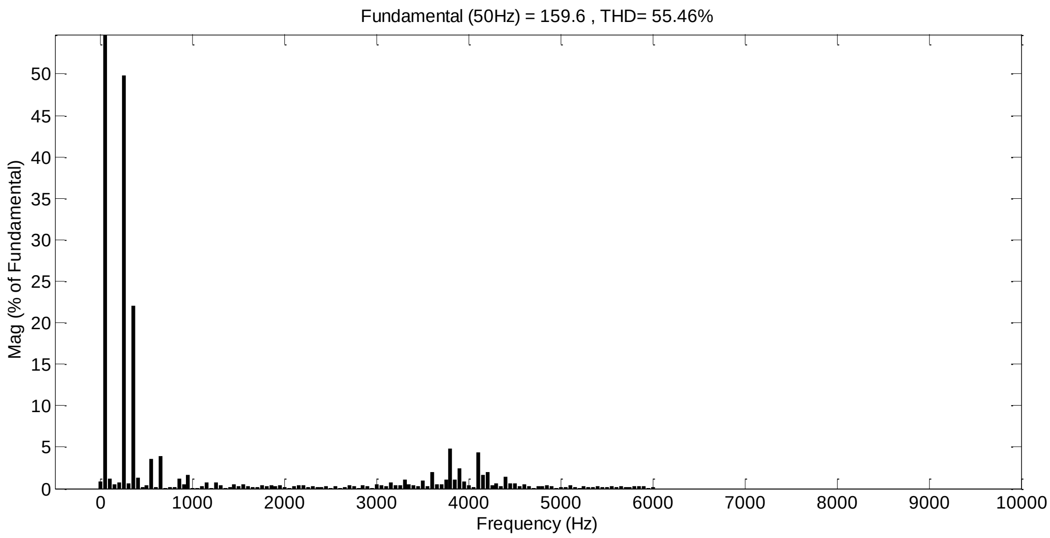

Figure 10. FFT of input current.

Table IV. Voltage distortion limits at PCC (IEEE, 2014).

Bus voltage V	*Individual harmonic (%)*	*Total harmonic distortion THD (%)*
V≤1.0kV	5.0	8.0
1kV<V≤69kV	3.0	5.0
69kV<V≤161kV	1.5	2.5
161kV<V	1.0	1.5

Table V. Current distortion limits for general distribution systems (IEEE, 2014).

I_{sc}/I_1	*Odd harmonic order h (%)*					*Total Harmonic Distortion (%)*
	h<11	*11≤h<17*	*17≤h<23*	*23≤h<35*	*35≤h*	
<20	4.0	2.0	1.5	0.6	0.3	5.0
20-50	7.0	3.5	2.5	1.0	0.5	8.0
50-100	10.0	4.5	4.0	1.5	0.7	12.0
100-1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

The effect of this distorted supply current on the supply voltage waveform (due to the presence of the supply side impedance) is seen in Figure 11. Figure 12 shows the harmonic spectrum of this voltage waveform at the Point of Common Coupling (PCC), showing a THD of 5.33%. This level of harmonic content at the input is unacceptable, as this imposes voltage distortion to other consumers connected at the same point. A distorted voltage will in turn cause distorted currents to flow, which can cause improper operation for connected equipment. The high frequency currents also impose additional losses on the utility transformers, as well as increasing the overall loading due to higher RMS currents.

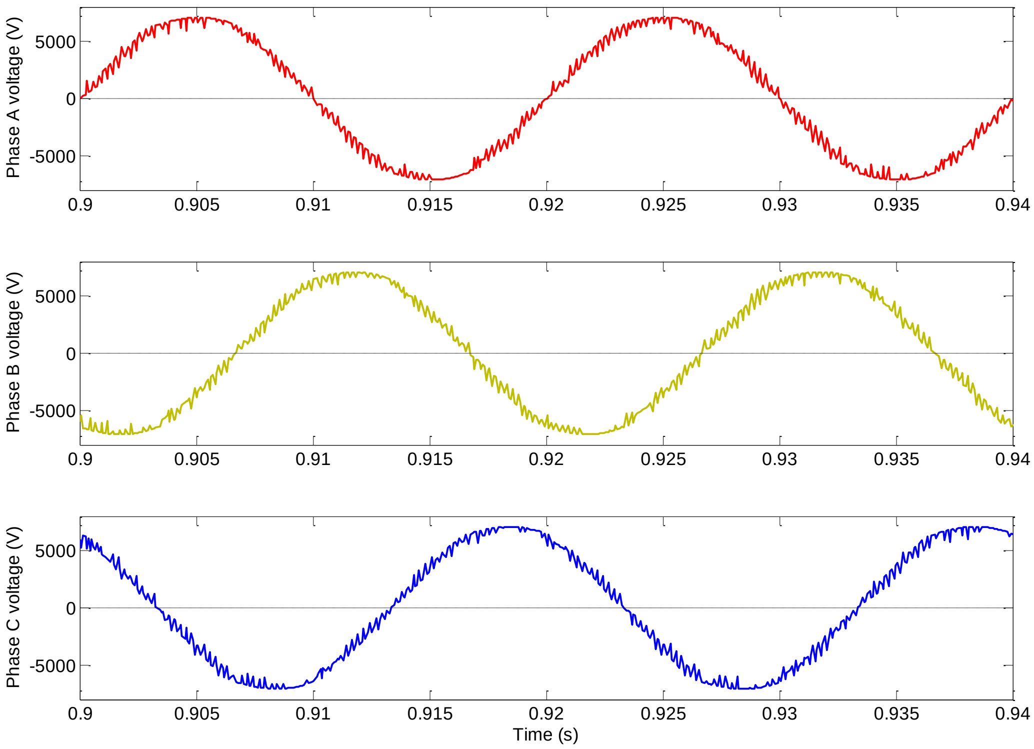

Figure 11. Voltage at Point of Common Coupling (PCC).

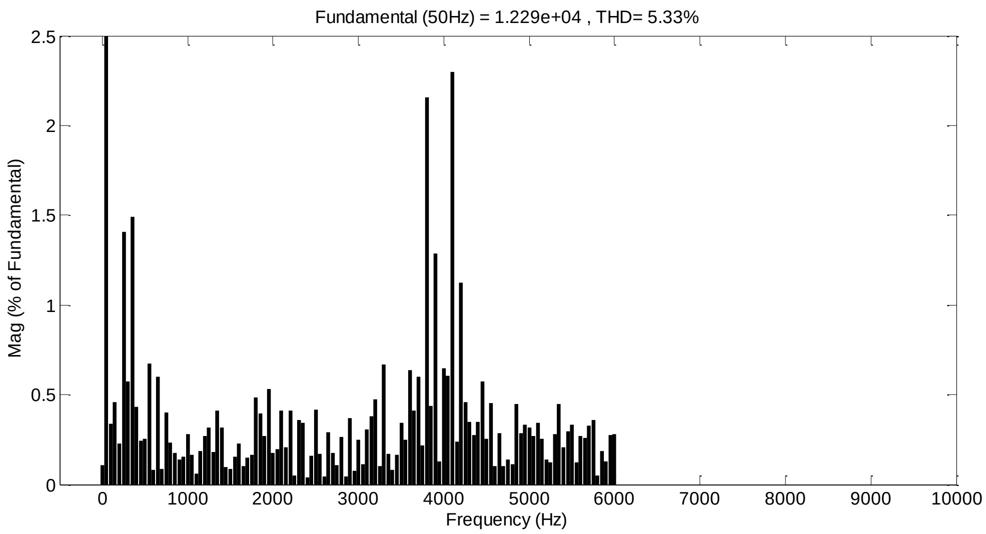

Figure 12. FFT of voltage at point of common coupling.

4.2. Operating characteristics at different loading conditions

The system must be able to operate satisfactorily at various loadings and conditions since the different vessels will have a power demand commensurate to their size and type. This power will also vary for the same vessel depending on other factors such as season (winter vs summer loads) or operating condition (loading/unloading/hotelling only). Table VI and Table VII show the steady state characteristics at various snapshots of the operating profile of Figure 3, with a number of different loads and vacant berths. The results show how the output THD levels as well as the steady state voltages meet the required levels. The input characteristics on the other hand are still unacceptable, injecting significant harmonics onto the utility supply network.

Table VI. Loading at time 43hrs.

Berth number	*Load (kVA)*	*Line Voltage (V)*	*Deviation from nominal*	*Voltage THD at berth*
1	0	6,599	0.0%	0.48%
2	0	6,599	0.0%	0.48%
3	1,000	6,412	2.8%	0.38%
4	0	6,599	0.0%	0.48%
5	750	6,435	2.5%	0.39%
			Input current THD	48.58%
			Voltage THD at PCC	7.61%
			Overall energy efficiency	89.5%

Table VII. Loading at time 80hrs.

Berth number	*Load (kVA)*	*Line Voltage (V)*	*Deviation from nominal*	*Voltage THD at berth*
1	500	6,459	2.1%	0.53%
2	900	6,422	2.7%	0.52%
3	900	6,429	2.6%	0.52%
4	400	6,566	0.5%	0.53%
5	0	6,599	0.0%	0.60%
			Input current THD	53.53%
			Voltage THD at PCC	6.82%
			Overall energy efficiency	90.6%

The provision of a cold ironing connection can therefore supply the onboard demanded energy of berthed ships with the required electrical characteristics and power quality. However, significant power quality issues have been highlighted in this study with respect to the utility supply network and these must be considered in detail before any such arrangements are made as the amount of harmonics introduced by the uncompensated system reaches unacceptable levels. This issue must be addressed and the quality of supply guaranteed at different loading levels according to the expected power demands from the various berthed ships.

4.3. Transient considerations

Steady-state stability and RMS voltage and current values within acceptable limits are extremely important considerations for stable and secure cold ironing operation that meets the requirements of both parties involved. The power profiles of Figure 3 are averaged quantities which are indicative of the average power demands of the berthed vessels. The actual load profiles (Figure 2) will show more fluctuations and variations due to the intermittent nature of the onboard loads. The switching on/off of loads will induce oscillations which must not adversely affect the rest of the system. Limits on transient conditions are set out in (IEC/ISO/IEEE, 2012) as being +20% and -15% for voltage excursions from nominal for the largest expected load step. This expected load step when berthed is to be documented for each ship which must then be matched to the expected response from the shore supply to ensure that limits are respected.

Figure 13 shows the responses of the RMS value of the output voltage to a ±50% step change in load on berth 1. In all cases, the output voltage is maintained within the transient limits indicated by the dotted lines on the plot. The perturbation was observed at the berth connections, in order to examine the effect a load transient onboard the ship would have on the actual terminal voltage. The transient response will of course be different for different installations, depending on the dynamic characteristics of the frequency converter implemented, influenced by controller time constants and the values of passive circuit components.

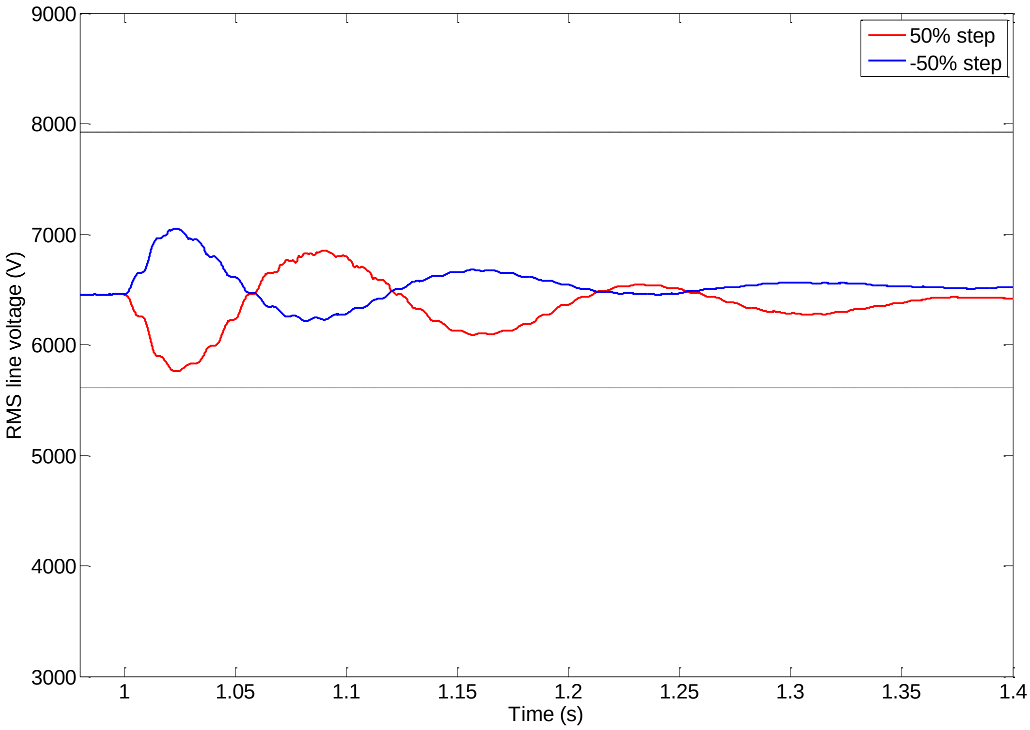

Figure 13. Transient response of phase voltage at berth 1 in response to a ±50% load step change at time 1s; The dotted lines indicate the +20%/-15% permitted limits for transient conditions.

4.4. Harmonic Mitigation

Various measures can be taken to improve the utility connection so that it meets the required standards. The connection of a passive filter at the input (similar to the way the output of the converter is filtered) is a possible solution (LCL filter shown as Figure 14 a), but large values of passive components are required. An active front end (Figure 14 b) can be used instead of the uncontrolled diode bridge rectifier. This takes the form of the controlled inverter stage replicated at the input stage. Having controlled switches at the input gives numerous benefits, including a much smaller DC link ripple (or a corresponding DC capacitor size reduction) giving also a cleaner input (and hence smaller input filter). The input currents can be controlled, such that the power factor is controlled to be unity. This does come at the significant expense of an additional controlled power electronic stage. Another power electronic option would be to install an active filter, which utilises a current-mode controlled power electronic converter to counter the input distortion current, minimising the use/size of passive components (Figure 14 c). This, however, is a more expensive and less efficient option, when compared to passive filters (Akagi, 2005).

Another solution which offers reduced current distortion at the input is the use of a higher pulse-number rectifier. A 12-pulse rectifier (Figure 14 d) makes use of a transformer with both a star and a delta connected output winding to utilise the 30° phase difference between the voltage waveforms of the two sets of windings. This produces twelve DC pulses per supply cycle (compared to the six pulses produced by a standard three-phase rectifier circuit) and a stepped AC current waveform eliminating all harmonics below 550 Hz (the 11^{th} harmonic) for a lower input current THD. A 24-pulse arrangement can be produced by combining two 12-pulse systems with a 15° phase shift between the primary windings. This will produce 24 DC pulses per supply cycle, and a much smoother AC current waveform, eliminating all current harmonics below the 23^{rd}.

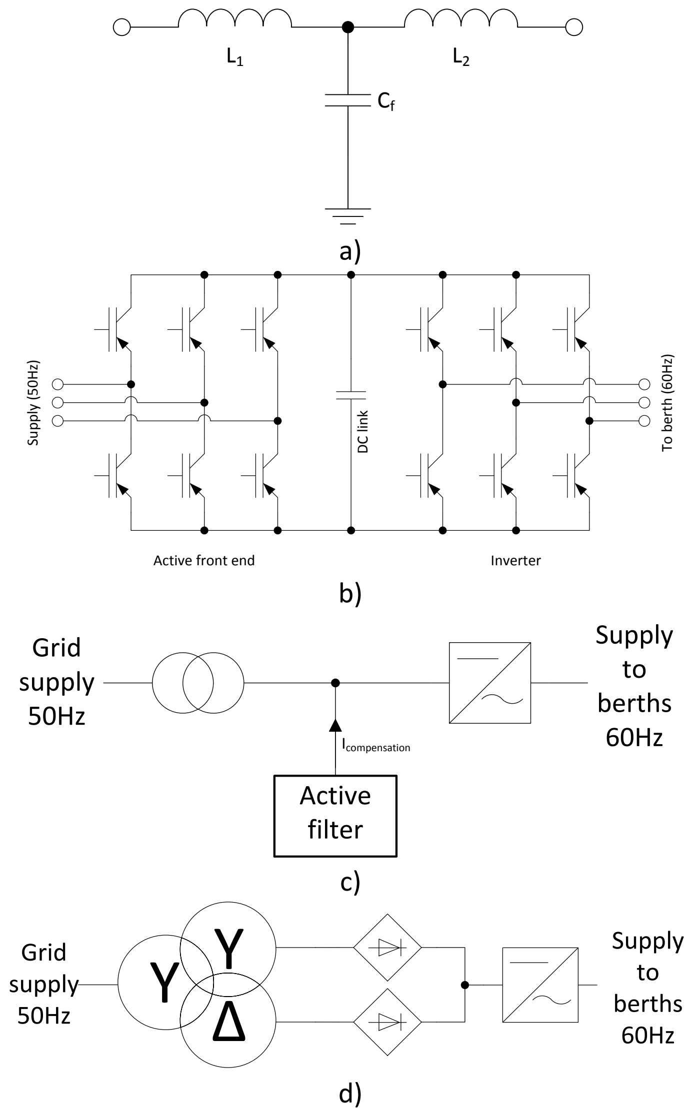

Figure 14. Harmonic mitigation techniques; a) LCL filter, b) active front end rectifier, c) active filter and d) twelve pulse rectifier.

5. Conclusions

Airborne emissions are of particular concern in harbour areas due to the proximity of vessel operations to human habitation. Cold ironing permits berthed vessels to shut down their onboard auxiliary generators to provide a locally emission-free solution by shifting the energy generation to the shore supply. The net resultant emissions will be dependent on the location of berthing, and the generation mix of the energy sources employed on shore.

A centralised cold ironing topology with a single frequency converter able to provide power to a multiple berth port was previously shown to be the most suited in this instance for minimisation of energy demand. This scenario considers actual loading data over a ninety hour period, from a five berth RoRo terminal such that realistic profiles are used for simulation of the system's operation. In this paper, detailed models of the system were built in order to analyse the electrical characteristics of the configuration in question. A steady-state load flow analysis was performed, to ensure that berth voltages are within the permitted tolerances, as well as determination of the power quality at the output. The results show that the selected centralised system is able to meet the output requirements both in terms of steady state voltage values as well meeting harmonic distortion limits. However, the study has highlighted the significant harmonic content at the input of the shore connection system, with THD values in excess of acceptable limits. Clearly, the use of power electronics generates significant harmonic content which must be managed in order not to adversely affect other consumers connected to the same supply network. Operating within the required harmonic limits is a necessary precondition to connection and represents a shared responsibility between system operators and users.

The use of an onshore power supply is beneficial to the immediate harbour area, as the use of onboard generators is reduced. Yet it must be ensured that the onshore power supply system not have an adverse impact on the electrical utility, a process for which detailed simulations are well suited. After all, reducing airborne pollution must not come at the expense of increased electrical pollution.

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Nomenclature

ECA – Emission Control Area
FFT – Fast Fourier Transform
HVSC – High Voltage Shore Connection
IGBT – Insulated Gate Bipolar Transistor
LNG – Liquefied Natural Gas
LVSC – Low Voltage Shore Connection
PCC – Point of Common Coupling
PI Controller – Proportional and Integral Controller
PSO – Particle Swarm Optimisation
PWM – Pulse Width Modulation

RMS – Root Mean Squared
RoRo – Roll-On Roll-Off
THD – Total Harmonic Distortion

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